

Plate Efficiency in Petroleum Fractionating Columns

By
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A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN THE UNIVERSITY OF MICHIGAN

Ann Arbor, Michigan
1934

[Reprinted from Industrial and Engineering Chemistry, Vol. 28, Page 824, July, 1936.]





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DESIGN OF

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The over-all plate efficiency in commercial petroleum columns treating gasoline or light naphthas under efficient operating conditions is close to 100 per cent. With close plate spacing or short path of reflux on plates, the efficiency is decreased to about 80 per cent. In lower sections of petroleum columns, or when operating on less volatile fractions, the plate efficiency is progressively reduced. With poor operating conditions, such as large quantities of water on plates, the plate efficiency is seriously limited and may be reduced to about 15 per cent.

The graphical method of computing the number of equilibrium plates required to separate complex mixtures, such as petroleum, is convenient and reliable when limited to a section containing not more than six or eight equilibrium plates, and may be used in conjunction with over-all plate efficiencies to compute the number of actual plates required in a petroleum fractionating column.

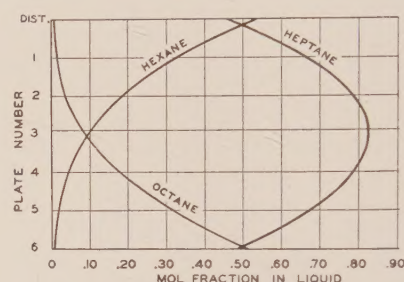


FIGURE 1. UNDERWOOD'S LIQUID COMPOSITIONS FOR TOTAL REFLUX PROBLEM

WHERE sharp separation between components is required, as is usually the case in gas and gasoline fractionation, a procedure similar to that previously described (4) is recommended for computing the number of equilibrium plates, or a more complete procedure (26) may be used, when time permits, for checking an assumed operation. In cases where less sharp separation between adjacent components, or a smaller number of plates between products, is required, as in current commercial practice in petroleum fractionation, the procedure to be described offers the advantage of greater simplicity.

The graphical method of McCabe and Thiele (19) is most satisfactory for its intended application to binary mixtures when the reflux ratio may be assumed to be constant. Attempts to apply an equivalent graphical procedure to complex mixtures have not been successful.

Fenske (6) and Garton and Huntington (9) have assumed that the fractionation between two cut components in the complex mixture is the same as though the two cut components alone were present in the same proportion, and that the reflux ratio of all components for the complex mixture is equivalent to the same reflux ratio for the two cut components alone for the equivalent binary mixture. This simplification is valid only for total reflux or for an infinite number of plates (3, 28), and is generally unreliable.

Obryadchikov (21) and Peters and Obryadchikov (23) used a single equilibrium curve based on the composition of the feed to a fractionating column to compute, by a graphical method similar to that of McCabe and Thiele (19), the number of plates required to separate the feed into overhead and bottom fractions containing certain percentages boiling below (or above) a chosen cut temperature. Adjustments in the slope of the operating lines were made at each plate for the changes in reflux ratio, and apparently satisfactory results were obtained by a somewhat obscure procedure, using Engler

distillation data. Attempts to apply the method, as described, to an entire column on the basis of either A. S. T. M. or so-called true-boiling-point distillation analyses have been unsuccessful. The difficulty lies in the attempted use for all plates of a single equilibrium curve based on the feed composition, which can express accurately the equilibrium conditions only for a mixture of the same composition as the feed. Since the shape of the equilibrium curve depends upon the composition of the material (13), which differs from plate to plate throughout the column and is at no point therein the same as the feed, successful application of this method requires the use of equilibrium curves depending upon the composition on the plates where the equilibrium is supposed to exist and not upon the composition of the feed.

Application to Underwood's Data

For example, the solution given by Underwood (28) for the fractionation of a mixture of five components may be correctly solved by a simple graphical procedure only if the proper equilibrium curve is used for each equilibrium plate. The conditions of this problem as solved by Underwood are given in Table I, and the compositions on plates 1 through 6, as computed by Underwood, are plotted in Figure 1.

TABLE I. SPECIFICATIONS FOR UNDERWOOD'S PROBLEM (28)

Component	Mole Fraction in:		
	Feed	Overhead	Bottoms
Hexane	0.3100	0.5360	...
Heptane	0.2600	0.4600	0.00126
Octane	0.1870	0.00406	0.4370
Nonane	0.1250	...	0.2960
Decane	0.1120	...	0.2660
Moles/mole of overhead	1.7310	1.0000	0.7310
Total pressure = 14.7 lb./sq. in.; column operated at total reflux (L/V = 1).			

FRACTIONATING COLUMNS

III. Plate Efficiency and Number of Plates for Petroleum Columns²

Figure 2 is a plot, or graphical solution, of the composition on each of plates 1 through 6 according to the conditions set up in Table I, using the equilibrium curve for each plate as determined by Raoult's law from the known composition and temperature of the vapor rising from that plate. Since the column is operated with total reflux ($L/V = 1$), the composition of the liquid overflowing from any plate is the same as that of the vapor rising to that plate. The composition of the overhead vapor is given in Table I. By means of the equations (13),

$$\sum \left(\frac{y}{K} \right) = 1$$

$$\text{and } y = Kx$$

where $K = \frac{p}{P}$ when Raoult's law is used

p = vapor pressure of a particular component at equilibrium temp.

P = total pressure of equilibrium

the temperature of the top plate and the composition of the liquid overflowing from that plate are determined.

The numbered points in Figure 2 refer to the composition on the plate of that number for a particular cut temperature. The plain numbers (toward the upper right-hand corner) indicate the combined mole fraction of hexane plus heptane as a single component, while the primed numbers (toward the lower left-hand corner) indicate the mole fraction of hexane. The cut in the former case is made between heptane and octane, and in the latter between hexane and heptane; i. e., the two arbitrary components of the equivalent binary mixture are, in the first case, octane and all more volatile material; and in the second instance, hexane and all less volatile material.

By the use of the two series of steps, one representing the cut between octane and more volatile material (hexane and heptane) and the other between hexane and less volatile material (heptane and octane), the entire composition on each plate is represented by Figure 2 in a manner similar to that used by McCabe and Thiele for binary mixtures. The equilibrium curve for plate 2 only is drawn in its entirety, but it is clear that reliable results could not be obtained if any one of the six equilibrium curves were used to represent the conditions on all plates. When the correct equilibrium curve is used for each plate, the graphical principle of McCabe and Thiele, with all of its conveniences can be applied with accurate results to the fractionation of complex mixtures. But the difficulties in constructing a separate equilibrium curve from the composition of the vapor or liquid for each plate rob the method of all its conveniences.

Over a limited number of plates such as a short fractionat-

ing column or a section of a tall column, including usually not more than about six or eight equilibrium plates, it was found that the equilibrium curves for the materials on the intermediate plates are usually intermediate to, and lie within the area bounded by, the equilibrium curves for the first and last plates of the section. It was also found that such intermediate curves may be located with sufficient accuracy in this intermediate zone by proportional spacing of the abscissas (or ordinates), according to the number of intermediate plates.

This procedure was applied to a second problem set up by Underwood (28) in which the feed, overhead, and bottoms are of the same composition as given in Table I, but the reflux ratio (L/V) is 0.75. Underwood also computed the composition of the liquid on plate 6, which will be used as the lower terminal plate. The proposed binary mixture method is illustrated in Figure 3 in which the graphical solution is given for the mole fraction of hexane on the various plates in solid lines. The number of equilibrium plates required for this separation between hexane and the less volatile material (heptane and octane) as computed by the graphical method is six, the same as computed by Underwood.

The number of equilibrium plates required for the separa-

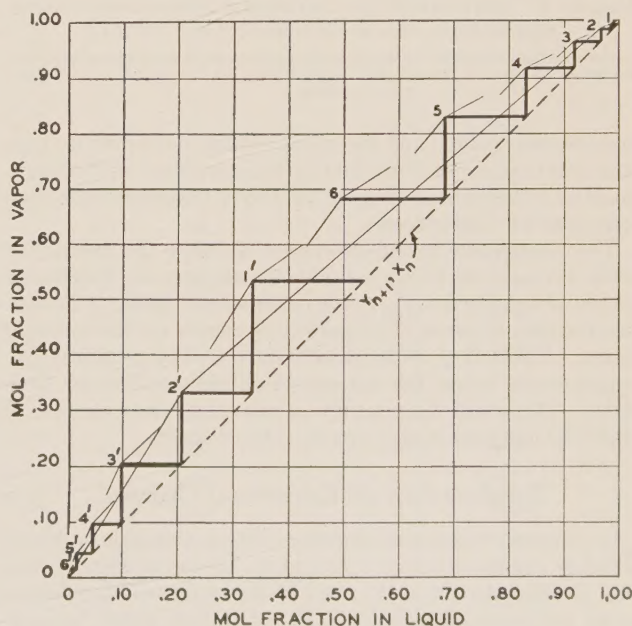


FIGURE 2. PLOT OF PLATE-TO-PLATE CALCULATIONS FOR UNDERWOOD'S TOTAL REFLUX PROBLEM

Plain numbers refer to equilibrium plate compositions for hexane plus heptane, as a single component. Primed numbers refer to equilibrium plate compositions for hexane.

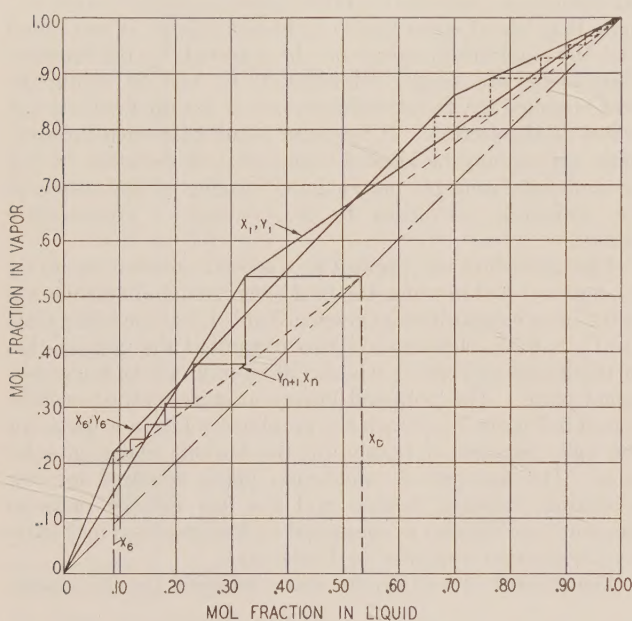
¹ Present address, Standard Oil Company, Casper, Wyo.

² Part I appeared in January, 1934, and Part II in April, 1935.

TABLE II. VAPOR AND LIQUID COMPOSITIONS FOR UNDERWOOD'S EXAMPLES (28)

Method 1 = Underwood's calculation for total reflux ($L/V = 1.0$).
 Method 2 = Hausbrand plate-to-plate calculation for total reflux ($L/V = 1.0$).
 Method 3 = graphical calculation for total reflux ($L/V = 1.0$), using empirical curves of Figure 4.
 Method 1A = Underwood's calculation for internal reflux (L/V) of 0.75.
 Method 2A = graphical calculation for internal reflux ratio (L/V) of 0.75.
 Method 3A = graphical calculation for internal reflux ratio (L/V) of 0.75, using empirical curves of Figure 4.

Component	Method	Mole Fraction of Component													
		y_1	x_1	y_2	x_2	y_3	x_3	y_4	x_4	y_5	x_5	y_6	x_6	y_7	x_7
$C_7H_{16} + C_6H_{14}$	1	0.9960	0.9860	...	0.9670	...	0.9175	...	0.8310	...	0.6820	...	0.4985	...	...
	2	0.9960	0.9860	0.9860	0.9650	0.9650	0.9175	0.9175	0.8300	0.8300	0.6830	0.6830	0.4975	...	...
	3	0.9960	0.9925	0.9925	0.9815	0.9815	0.9600	0.9600	0.9200	0.9200	0.8465	0.8465	0.7245	0.7245	0.5535
C_6H_{14}	1	0.5325	0.3360	...	0.1850	...	0.0930	...	0.0400	...	0.1500	...	0.0040	...	...
	2	0.5325	0.3325	0.3325	0.2040	0.2040	0.0980	0.0980	0.0410	0.0410	0.0185	0.0185	0.0060	...	...
	3	0.5325	0.3525	0.3525	0.2060	0.2060	0.1115	0.1115	0.0580	0.0580	0.0310	0.0310	0.0195	0.0195	0.0120
$C_7H_{16} + C_6H_{14}$	1A	0.9960	0.9860	...	...	...	...	...	...	...	...	...	0.7010	...	...
	2A	0.9960	0.9860	0.9880	0.9660	0.9735	0.9275	0.9440	0.8610	0.8954	0.7775	0.8315	0.6725	...	...
C_6H_{14}	1A	0.5325	...	...	...	...	...	...	...	...	...	...	0.0910	...	...
	2A	0.5325	0.3325	0.3810	0.2395	0.3100	0.1870	0.2705	0.1515	0.2440	0.1225	0.2200	0.0910	...	...
	3A	0.5325	0.3530	0.3980	0.2400	0.3125	0.1790	0.2670	0.1500	0.2450	0.1300	0.2300	0.1200	0.2200	0.1140

FIGURE 3. APPLICATION OF GRAPHICAL METHOD TO UNDERWOOD'S DATA FOR REFLUX RATIO (L/V) OF 0.75

Determination of number of equilibrium plates needed to obtain same fractionation as that indicated by Underwood's six computed equilibrium plates

tion between octane and the more volatile components (heptane and hexane) as computed by the graphical method indicated by dotted lines in Figure 3 is about 1.5 plates more than computed by Underwood.

The discrepancy in the latter case is due to the angularity of the curves when so few components are present, which may cause the equilibrium curve for intermediate plates to lie outside the area between the equilibrium curves for the terminal plates. Table II gives results obtained by the graphical procedure when using the correct equilibrium curve for each plate. The small discrepancy is caused by inaccuracies of graphical methods in the corners of the diagram.

Application of Empirical Curves

In instances where a minimum of data is available or where accuracy can be sacrificed for rapidity, the equilibrium curves may be estimated from the slope of the analytical distillation by an empirical relationship (13). Although these "empirical" curves, plotted in Figure 4, were originally based on the weight fraction of the feed material for an equilibrium vaporization, they may be used on a mole fraction basis when applied to the vapor or liquid in a section of a petroleum

column, and in the same manner as the more reliable equilibrium curves computed (13) from the actual composition of the liquid or vapor leaving the plate.

For example, the graphical solution of Underwood's problem for a reflux ratio (L/V) of 0.75 was made on Figure 4 (dotted lines) for the separation of hexane from the less volatile material (heptane and octane). Since the slope of the distillation curve of the material present on plate 6, according to Underwood's computations, would be zero if computed from the temperatures of the 10 and 70 per cent points, the slope was taken as between the initial and end points, or 102° F. per 100 per cent, or 1.02° F. per per cent. Both the overhead product and liquid on plate 6 have such slopes of 1.02; hence the one curve serves both the terminal and intermediate conditions.

It may be suggested that, because of the difficulty of properly interpolating for equilibrium curves of materials having distillation-curve slopes of less than 1.0, the curve for a slope of 1.0 be used for all fractions having slopes of 1.0 or less.

The dotted lines on Figure 4 suggest a difficulty that is sometimes experienced with these empirical curves. The operating line intersects the equilibrium curve at or before the point where the desired lower terminal composition is reached, because the equilibrium curves represent only approximately the terminal plate materials. Consequently the result of the determination in this instance is somewhat in doubt, approximately seven or eight plates being indicated as

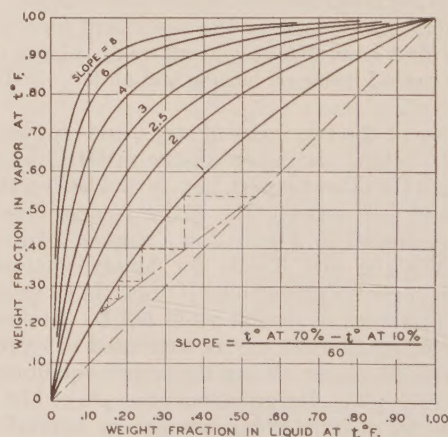


FIGURE 4. EMPIRICAL EQUILIBRIUM CURVES OF KATZ AND BROWN

Numbers on the curves refer to the slope of the so-called true-boiling-point distillation curves, in ° F. per per cent. Dotted lines indicate application of the curves to the graphical determination of the number of equilibrium plates required for the problem set up by Underwood (28) for reflux ratio (L/V) of 0.75

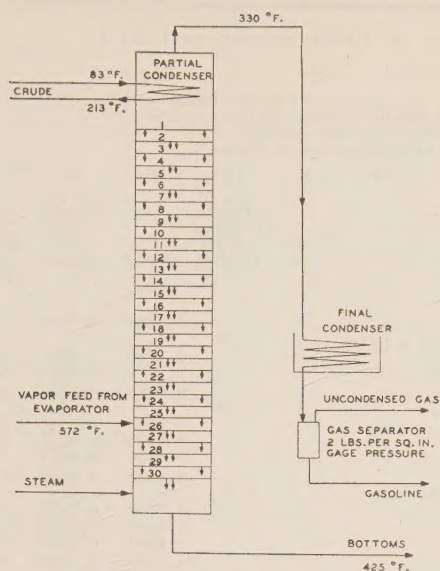


FIGURE 5. FLOW DIAGRAM OF UNIT 1 UNDER TEST

necessary to accomplish the desired separation, as against six computed by the more accurate methods.

Application to Petroleum Columns

The practical value of any method can be determined only by successful application to commercial operations. Complete test data were obtained on a commercial column, designated as unit 1, operating on a naphtha fraction of a California crude. Figure 5 gives a diagrammatic flow sheet of this unit under test. This fractionating column is 8 feet 7 inches in diameter and contains thirty plates spaced 12 inches apart. Vapors were supplied from an evaporator in which the crude was separated into 51 per cent residuum and 49 per cent vapor feed which entered the column between plates 25 and 26, and was fractionated into an overhead product and bottoms. Reflux for the separation was furnished by passing the cold crude through a partial condenser located in the vapor space above plate 1.

The operating test data are presented in Figures 6 and 7, and Table III. The molecular weights were determined from published data (7, 18), as were the specific, sensible, and latent heats (8, 14, 30, 31).

The usual equations (29) employed in making the Hausbrand type (12) of plate-to-plate computation were applied to the experimentally determined composition of the liquid overflowing from plate 1 to compute the composition and quantity of the vapor rising from plate 2 rather than attempting to use the undetermined composition of the stream from the reflux condenser as a starting point. The composition and temperature of the liquid on equilibrium plate 2 was next computed by the application of a corrected Raoult's law (1) to the composition of the vapor rising from plate 2, in the manner shown in Table IV (13). This procedure was then repeated for equilibrium plates 3, 4, and 5. The results of these calculations are given as method 1 in Table V and in Figure 8.

The graphical method was then applied to the same problem, using identical vapor-liquid equilibrium data for equilibrium plates 2 and 5, as illustrated in Figure 9. The value of

TABLE III. TEST DATA FOR UNIT 1

Stream	Gravity, ° A. P. I.	Temp., ° F. Liquid	Temp., ° F. Vapor	Quantity/Hr.	Gage Pressure, Lb./Sq. In.
Crude	31.1	614	...	209 bbl.	..
Residuum	19.8	566	...	107 bbl.	..
Naphtha feed	44.9	572	...	102 bbl.	..
Bottoms	33.7	425	...	335 bbl.	..
Distillate	51.6	...	330	68.4 bbl.	..
Liquid on:					
Plate 1	42.3	363	359	...	6.5
Plate 2	41.8	397	...	...	..
Plate 3	40.8	414	...	...	..
Plate 5	40.3	423	...	...	..
Plate 9	39.9	436	...	...	..
Plate 13	39.5	440	...	...	..
Plate 16	39.4	441	...	...	..
Plate 19	39.2	447	...	...	..
Plate 21	38.5	...	455	...	..
Plate 23	37.6	461	467	...	..
Plate 25	35.5	485	492	...	..
Plate 26	35.0	481	527	...	18.0
Plate 28	34.2	...	...	...	..
Plate 30	35.2	455	444	...	..
Steam	..	...	...	530 lb.	..

L/V for use in this analysis was obtained by averaging the L/V ratios found for plates 2, 3, and 4 by the plate-to-plate calculations. Using this average value of 0.568 for the slope, the operating line was laid off, passing through the point (x_1, y_2) for the arbitrarily selected cut temperature, and the number of equilibrium plates required was stepped off as previously described. The two operating lines in Figure 9 represent the two cut temperatures of 425° and 390° F. Similar operating lines were laid off for each cut temperature shown in Table V, and the required number of equilibrium plates was stepped off to obtain the same separation as in the case of the four equilibrium plates of the plate-to-plate calculation. The

TABLE IV. COMPUTATION OF VAPOR-LIQUID EQUILIBRIUM ON PLATE 5 OF UNIT 1

Temp. ° F.	Mole Fraction in Liquid x	Δx	Av. Atm. B. P. ° F.	Vapor Pressure (2) at 425° F. Mm. Hg	$K \cdot \Delta x$	Mole Fraction in Vapor y
160	0	0.02	202	10,550	0.1690	0.1663
228	0.02	0.02	250	6,200	0.0984	0.0969
265	0.04	0.02	282	4,290	0.0680	0.0670
293	0.06	0.02	305	3,255	0.0516	0.0509
317	0.08	0.02	335	2,273	0.0721	0.0710
353	0.12	0.04	365	1,600	0.0508	0.0500
374	0.16	0.06	383	1,265	0.0602	0.0593
390	0.22	0.06	395	1,100	0.0524	0.0515
399	0.28	0.06	402	992	0.0473	0.0465
405	0.34	0.06	409	930	0.0443	0.0435
414	0.40	0.06	422	775	0.0369	0.0363
424	0.46	0.06	425	760	0.0362	0.0356
426	0.52	0.06	429	730	0.0348	0.0342
430	0.58	0.06	433	695	0.0330	0.0324
436	0.64	0.06	439	648	0.0308	0.0303
441	0.70	0.06	442	605	0.0288	0.0283
445	0.76	0.06	447	575	0.0273	0.0268
449	0.82	0.04	449	555	0.0176	0.0173
450	0.86	0.04	450	550	0.0173	0.0170
450	0.90	0.04	451	545	0.0171	0.0168
452	0.94	0.04	456	515	0.0162	0.0159
465	0.98	0.02	474	400	0.0063	0.0062
492	1.00					1.000
				Total	1.0164	1.0000

* $K = 0.88 p/P$; $P = 1110$ mm. Hg.

TABLE V. EQUILIBRIUM PLATES AND PLATE EFFICIENCY IN UPPER SECTION OF UNIT 1

Method 1 = plate-to-plate calculation for 4 equilibrium plates (Raoult's law correction factor = 0.88).
Average reflux ratio (L/V) = 0.568 for following methods:
Method 2 = graphical calculation using same terminal plates as found by method 1 (Raoult's law correction factor = 0.88).
Method 2A = graphical calculation from actual plate 2 through actual plate 5 (Raoult's law correction factor = 0.88).
Method 2B = graphical calculation from actual plate 2 through actual plate 5 (Raoult's law unmodified).
Method 3 = graphical calculation from actual plate 2 through actual plate 5, using empirical curves of Figure 4.

Cut Temp. ° F.	Method	Mole Fraction of Arbitrary Component														15 No. of Plates to Equal x_1 of Method 1	16 Actual x_1	17 y_1 in Equilib- rium with Actual x_1	18 No. Equilib- rium Plates	19 Plate Effi- ciency %
		x_1	y_2	x_2	y_3	x_3	y_4	x_4	y_5	x_5	y_6	x_6	y_7	x_7	y_7					
445	1	0.9895	0.9926	0.9655	0.9791	0.9191	0.9023	0.7369	0.8478	0.6318	.....	.....	.....	.....	.....	.....	0.7600	0.8995	3.05	76
	2	0.9895	0.9926	0.9655	0.9790	0.9185	0.9520	0.8340	0.9040	0.7310	0.8460	0.6270	.....	.....	.....	4.97	0.7600	0.8995	4.50	111
	2A	.....	0.9926	.....	0.9810	.....	0.9565	.....	0.9200	.....	0.8790	.....	.....	.....	.....	.....	0.7600	0.9025	4.63	116
	2B	.....	0.9926	.....	0.9815	.....	0.9600	.....	0.9275	.....	0.8880	.....	.....	.....	.....	.....	0.6950	0.8690	2.88	72
440	1	0.9385	0.9629	0.8623	0.9199	0.7610	0.8622	0.6535	0.7988	0.5429	.....	.....	.....	.....	.....	.....	0.6950	0.8690	2.93	73
	2	0.9385	0.9629	0.8623	0.9190	0.7515	0.8560	0.6370	0.7910	0.5310	.....	.....	.....	.....	.....	3.88	0.6950	0.8720	2.87	72
	2A	.....	0.9629	.....	0.9195	.....	0.8640	.....	0.8075	.....	.....	.....	.....	.....	.....	.....	0.6950	0.8720	2.87	72
	2B	.....	0.9629	.....	0.9200	.....	0.8650	.....	0.8100	.....	.....	.....	.....	.....	.....	.....	0.6950	0.8975	2.20	55
425	1	0.9125	0.9416	0.7975	0.8768	0.6658	0.7994	0.5372	0.7253	0.4241	.....	.....	.....	.....	.....	.....	0.4900	0.7620	3.50	88
	2	0.9125	0.9416	0.7975	0.8765	0.6645	0.8010	0.5385	0.7295	0.4280	0.6670	.....	.....	.....	.....	.....	0.4900	0.7620	3.59	90
	2A	.....	0.9416	.....	0.8750	.....	0.8025	.....	0.7340	.....	.....	.....	.....	.....	.....	.....	0.4900	0.7650	3.59	90
	2B	.....	0.9416	.....	0.8755	.....	0.8050	.....	0.7375	.....	.....	.....	.....	.....	.....	.....	0.4900	0.7850	2.85	71
415	1	0.9057	0.9194	0.7408	0.8264	0.5871	0.7247	0.4178	0.6385	0.3042	.....	.....	.....	.....	.....	.....	0.4000	0.7070	3.21	80
	2	0.9057	0.9194	0.7408	0.8270	0.5755	0.7325	0.4245	0.6460	0.3150	0.5670	.....	.....	.....	.....	.....	0.4000	0.7070	3.28	82
	2A	.....	0.9194	.....	0.8255	.....	0.7300	.....	0.6480	.....	.....	.....	.....	.....	.....	.....	0.4000	0.7095	3.18	80
	2B	.....	0.9194	.....	0.8270	.....	0.7350	.....	0.6510	.....	.....	.....	.....	.....	.....	.....	0.4000	0.7095	3.18	80
405	1	0.8953	0.9075	0.7153	0.8059	0.5317	0.6986	0.3819	0.6119	0.2823	.....	.....	.....	.....	.....	.....	0.3380	0.6645	3.49	87
	2	0.8953	0.9075	0.7153	0.8065	0.5375	0.7045	0.3835	0.6175	0.2815	0.5600	.....	.....	.....	.....	.....	0.3380	0.6655	3.51	88
	2A	.....	0.9075	.....	0.8070	.....	0.7060	.....	0.6205	.....	.....	.....	.....	.....	.....	.....	0.3380	0.6780	2.94	74
	2B	.....	0.9075	.....	0.8070	.....	0.7080	.....	0.6245	.....	.....	.....	.....	.....	.....	.....	0.3380	0.6780	2.94	74
394	1	0.8151	0.8540	0.6157	0.7416	0.4399	0.6378	0.3091	0.5620	0.2208	.....	.....	.....	.....	.....	.....	0.2400	0.5835	3.72	93
	2	0.8151	0.8540	0.6157	0.7415	0.4305	0.6370	0.2995	0.5620	0.2208	.....	.....	.....	.....	.....	.....	0.2400	0.5835	3.69	92
	2A	.....	0.8540	.....	0.7375	.....	0.6350	.....	0.5600	.....	.....	.....	.....	.....	.....	.....	0.2400	0.5875	3.69	92
	2B	.....	0.8540	.....	0.7415	.....	0.6390	.....	0.5640	.....	.....	.....	.....	.....	.....	.....	0.2400	0.5875	3.69	92
390	1	0.6615	0.7639	0.4578	0.6490	0.3159	0.5631	0.2250	0.5101	0.1700	.....	.....	.....	.....	.....	.....	0.2180	0.5620	3.02	75
	2	0.6615	0.7639	0.4578	0.6480	0.3070	0.5620	0.2220	0.5125	0.1715	0.4860	.....	.....	.....	.....	.....	0.2180	0.5620	3.04	76
	2A	.....	0.7639	.....	0.6490	.....	0.5640	.....	0.5130	.....	.....	.....	.....	.....	.....	.....	0.2180	0.5680	2.98	75
	2B	.....	0.7639	.....	0.6500	.....	0.5660	.....	0.5135	.....	.....	.....	.....	.....	.....	.....	0.2180	0.5680	2.98	75
360	1	0.5512	0.6728	0.3312	0.5478	0.2074	0.4728	0.1423	0.4343	0.1090	.....	.....	.....	.....	.....	.....	0.1320	0.4625	3.27	82
	2	0.5512	0.6728	0.3312	0.5470	0.2050	0.4755	0.1435	0.4410	0.1140	0.4250	.....	.....	.....	.....	.....	0.1320	0.4625	3.38	85
	2A	.....	0.6728	.....	0.5485	.....	0.4750	.....	0.4425	.....	.....	.....	.....	.....	.....	.....	0.1320	0.4625	3.38	85
	2B	.....	0.6728	.....	0.5520	.....	0.4785	.....	0.4400	.....	.....	.....	.....	.....	.....	.....	0.1320	0.4800	2.98	75
340	1	0.3628	0.5420	0.2010	0.4507	0.1306	0.4048	0.0973	0.3845	0.0802	.....	.....	.....	.....	.....	.....	0.0930	0.4010	3.19	80
	2	0.3628	0.5420	0.2010	0.4515	0.1300	0.4115	0.1030	0.3965	0.0895	0.3880	0.0825	0.3840	.....	.....	.....	0.0930	0.4010	3.40	85
	2A	.....	0.5420	.....	0.4500	.....	0.4070	.....	0.3920	.....	.....	.....	.....	.....	.....	.....	0.0930	0.4010	3.40	85
	2B	.....	0.5420	.....	0.4510	.....	0.4085	.....	0.3905	.....	.....	.....	.....	.....	.....	.....	0.0930	0.4185	2.77	69
300	1	0.1972	0.3909	0.0962	0.3339	0.0664	0.3115	0.0533	0.3030	0.0465	.....	.....	.....	.....	.....	.....	0.0650	0.3410	1.88	47
	2	0.1972	0.3909	0.0962	0.3350	0.0675	0.3180	0.0575	0.3130	0.0520	0.3090	0.0485	0.3070	.....	.....	.....	0.0650	0.3410	1.87	47
	2A	.....	0.3909	.....	0.3335	.....	0.3155	.....	0.3120	.....	.....	.....	.....	.....	.....	.....	0.0650	0.3410	1.87	47
	2B	.....	0.3909	.....	0.3345	.....	0.3175	.....	0.3120	.....	.....	.....	.....	.....	.....	.....	0.0650	0.3520	1.59	40

compositions of the individual streams so computed are indicated under method 2 of Table V. The number of plates determined by this method, necessary to give the same fractionation as indicated by the four equilibrium plates of the plate-to-plate analysis are indicated in Table V, column 15.

A comparison of the composition of each stream as obtained by these two procedures, methods 1 and 2, indicates good agreement in all but a few cases at the extreme corners of the equilibrium curves. This difficulty encountered in the upper corner is due in part to the high sensitivity to small changes in the vapor composition, and in part to the difficulty in making sufficiently accurate geometrical construction in the small dimensions of the corner. Similar errors are also introduced in the lower corner.

A study of Table V indicates that cut temperatures with fractions of more than 0.97 or 0.98 in the material rising from the top terminal plate should not be used. Similarly, cut

temperatures with fractions less than 0.08 or 0.10 in the liquid on the lower terminal plate should not be used for reliable results. The average of the results of this graphical procedure (method 2, Table V), omitting the obviously incorrect values of the 445°, 340°, and 300° F. cuts for these reasons, indicates 4.12 plates required to accomplish the same fractionation as obtained by 4 plates as computed by the plate-to-plate procedure (method 1, Table V).

Another comparison of equilibrium plates was made in the lower section of the same column. In this case the plate-to-plate computations were begun with the liquid leaving plate 19 (Figure 7) and continued for three equilibrium plates. The procedure for calculating the vapor-liquid equilibria was somewhat modified from that followed in the upper section of the column. In this instance the equilibrium plate temperature was approximated and Raoult's law was applied, provisions being made for arbitrarily introducing on

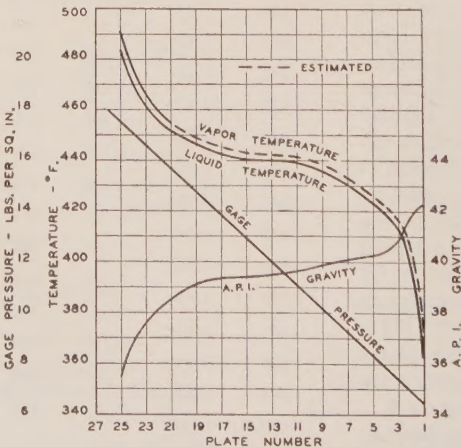


FIGURE 6. OPERATING CONDITIONS FOR UNIT 1 UNDER TEST

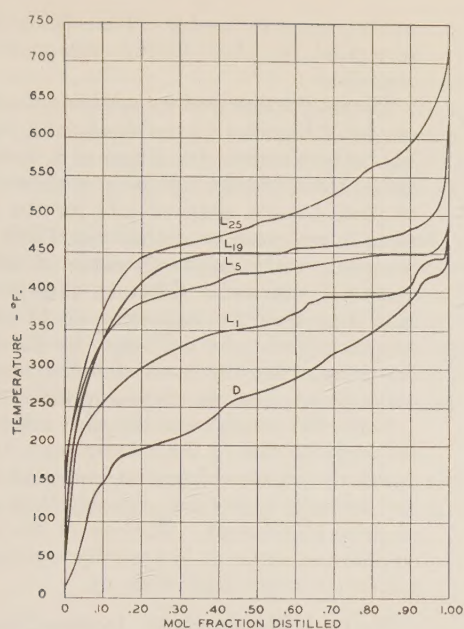


FIGURE 7. TRUE-BOILING-POINT DISTILLATION ANALYSES FOR UNIT 1

Compositions for overhead distillate and liquid leaving plates 1, 5, 19, and 25

each plate a proportional part of the heavier component present in the liquid from actual plate 25, but not appearing in the analysis of the liquid on plate 19. The results of the computation are given as method 1 in Table VI and in Figure 10.

The graphical method was applied to the identical equilibrium data as were used in these plate-to-plate computations for the lower section of the column, with the results given as method 2 in Table VI. The cut temperature of 555° F. gave excellent agreement with the plate-to-plate calculations, although representing more than 0.98 of the vapor rising from the upper terminal plate. The cut temperature of 400° F. represents less than 0.10 of the liquid on the lower terminal plate, and, for the reasons stated, is not expected to give reliable results. Excluding the cut temperature of 400° F., the graphical method indicates an average of 2.70 equilibrium plates for the same fractionation as calculated for 3 equilibrium plates by the plate-to-plate method.

The graphical calculations presented for the determination of the number of equilibrium plates required to effect a given

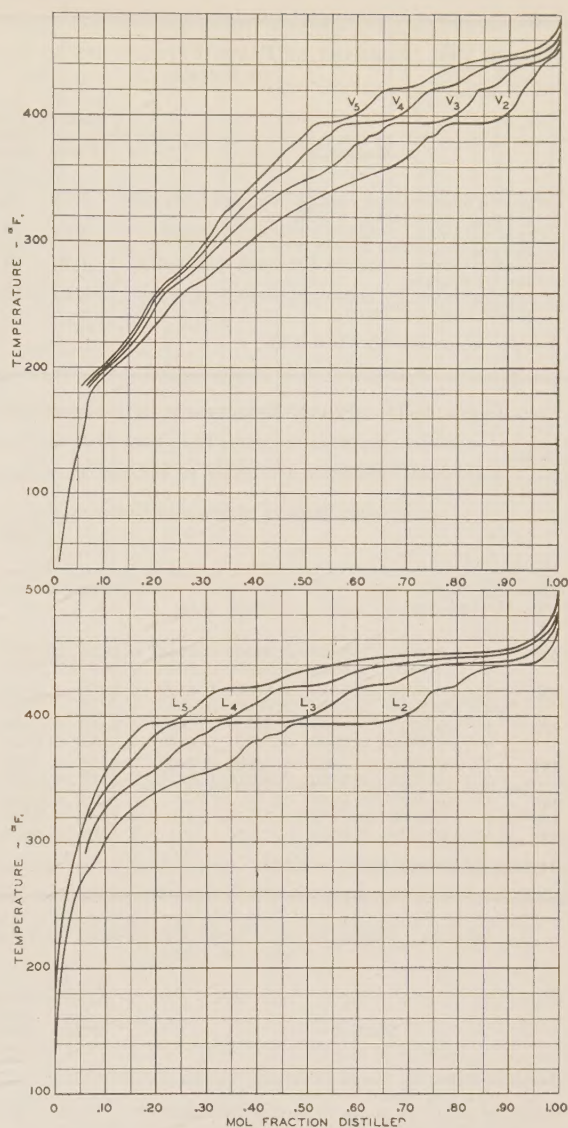


FIGURE 8. DISTILLATION CURVES FOR VAPORS AND LIQUIDS IN UPPER SECTION OF UNIT 1 AS CALCULATED BY PLATE-TO-PLATE METHOD

(Above) Computed vapors rising from equilibrium plates 2, 3, 4, and 5

(Below) Computed liquids leaving equilibrium plates 2, 3, 4, and 5

TABLE VI. COMPARISON OF EQUILIBRIUM PLATES IN LOWER SECTION OF UNIT 1

Method 1 = Hausbrand's plate-to-plate calculation for 3 equilibrium plates.
Method 2 = graphical calculation for same terminal plates as used in method 1 (average $L/V = 0.515$).

Cut Temp. ° F.	Method	Mole Fraction of Arbitrary Component						No. Equilibrium Plates
		x_1	y_2	x_2	y_3	x_3	y_4	
555	1	0.9962	0.9925	0.9466	0.9725	0.8482	0.9231	3.00
	2	0.9962	0.9925	0.9466	0.9715	0.8500	0.9225	2.95
488	1	0.9390	0.9677	0.8570	0.9264	0.7116	0.8539	3.00
	2	0.9390	0.9677	0.8570	0.9260	0.7000	0.8445	2.85
475	1	0.8480	0.9199	0.7462	0.8694	0.6014	0.7981	3.00
	2	0.8480	0.9199	0.7462	0.8670	0.5625	0.7725	2.75
460	1	0.6585	0.8202	0.5588	0.7730	0.4494	0.7211	3.00
	2	0.6585	0.8202	0.5588	0.7685	0.4545	0.6895	2.60
452	1	0.4986	0.7352	0.4180	0.6996	0.3144	0.6518	3.00
	2	0.4986	0.7352	0.4180	0.6945	0.3030	0.6350	2.70
439	1	0.3002	0.6295	0.2601	0.6171	0.2112	0.5982	3.00
	2	0.3002	0.6295	0.2601	0.6085	0.2030	0.5785	2.35
400	1	0.1694	0.5235	0.1446	0.5194	0.1207	0.5136	3.00
	2	0.1694	0.5235	0.1446	0.5100	0.1130	0.4945	1.65
Average, method 1 (excluding 400° F. cut)								3.00
Average, method 2 (excluding 400° F. cut)								2.70

separation agree within about ± 10 per cent with the plate-to-plate computations. The equilibrium curves for the material on the top and bottom terminal plates of a short section of any column may be used as the limits for the equilibria on intermediate plates, and these equilibria on intermediate plates may be estimated in the manner described. However, there is a limitation in selecting the cut temperatures to be used, because of the limitations of accuracy with which drawings and analyses can be made.

Plate Efficiency

The matter of plate efficiency has been investigated from two distinctly different approaches, the average individual plate efficiency (20), and the over-all plate efficiency. The former is derived from a consideration of the individual plate efficiency of each plate in a column. The latter is the quotient of the total number of

TABLE VII. SUMMARY OF PLATE EFFICIENCIES AT UPPER SECTION OF UNIT 1^a

Method	Av. No. Equilibrium Plates	Av. Plate Efficiency %	Cut Temp. Included in Av. ° F.
1. Plate-to-plate calcn. for plates 2 through 5 (Raoult's law correction factor = 0.88)	3.28	82	440, 425, 415, 405, 394, 390, 360
2A. Graphical calcn. for plates 2 through 5 (Raoult's law correction factor = 0.88)	3.35	84	440, 425, 415, 405, 394, 390, 360
2B. Graphical calcn. for plates 2 through 5 (Raoult's law unmodified)	3.26	82	440, 425, 415, 405, 394, 390, 360
3. Graphical calcn. for plates 2 through 5, using empirical curves of Fig. 1	2.78	70	440, 425, 405, 390

^a Average reflux ratio (L/V) = 0.568.TABLE VIII. PLATE EFFICIENCY IN BOTTOM OF UNIT 1^a

Method 1 = graphical calculation for plates 19 through 25 (Raoult's law correction factor = 0.88).

Method 2 = graphical calculation for plates 19 through 25, using empirical curves of Figure 4.

Mole Fraction of Arbitrary Component						No. Equilibrium Plates	Plate Efficiency %
Cut Temp. ° F.	Method	x_{19}	y_{20}	y_{21}	y_{22}	Actual x_{25}	y_{25} in equilibrium with actual
520	1	0.9800	0.9820	0.9490	0.8750	0.6650	0.9400
	2	0.9800	0.9820	0.9550	0.9000	0.6650	0.9280
490	1	0.9350	0.9510	0.9080	0.8190	0.5070	0.8720
	2	0.9350	0.9510	0.8900	0.7820	0.5070	0.8650
476	1	0.8740	0.9000	0.8435	0.7605	0.4250	0.8280
	2	0.8740	0.9000	0.7970	0.6700	0.4250	0.8220
464	1	0.7300	0.7800	0.7090	0.5960	0.3210	0.7620
	2	0.7300	0.7800	0.6350	0.5325	0.3210	0.7500
456	1	0.5980	0.6850	.....	.....	0.2590	0.7180
440	1	0.3000	0.4110	.....	.....	0.1890	0.6620
420	1	0.2130	0.3630	.....	.....	0.1510	0.6300

^a Average reflux ratio (L/V) = 0.515.TABLE IX. SUMMARY OF PLATE EFFICIENCY FOR LOWER SECTION OF UNIT 1^a

Method	Av. No. Equilibrium Plates	Av. Plate Efficiency %	Cut Temp. Included in Av. ° F.
1. Graphical calcn. for plates 19 through 25 (Raoult's law correction factor = 0.88)	1.99	33	520, 490, 476, 464
2. Graphical calcn. for plates 19 through 25, using empirical curves of Fig. 1.	1.92	32	520, 490, 476, 464

^a Average reflux ratio (L/V) = 0.515.

equilibrium plates required to perform a desired separation, divided by the total number of actual plates required, and is the plate efficiency considered in the following calculations.

Plate Efficiency in Upper Section of Unit 1

In graphically determining the plate efficiency in the top section of unit 1, the equilibrium curves were computed for the actual materials on the second and fifth plates by means of Raoult's law, with a correction factor of 0.88. Operating lines were constructed for the cuts shown in Table V, using the average operating-line slope of 0.568. The number of equilibrium plates necessary to arrive at the actual fractionation effected in the column were stepped off between these operating lines and the computed equilibrium curves for the terminal plates, estimating the equilibria for the intermediate plates in the manner previously described. The results are given as method 2A in Table V, with the over-all plate efficiencies given in column 19.

In order to determine the effect of the Raoult's law correction factor (f) on computed plate efficiency, the same determinations were repeated, but with equilibrium curves computed by Raoult's law without a correction factor. The

results, given as method 2B in Table V, clearly show that the effect of the correction factor is negligible.

The results obtained by applying the empirical curves of Figure 4 to the same data, interpolating between curves for slopes of 1, 2, and 2.5 to obtain the curves for a slope of 2.33 for the liquid on plate 1 and a slope of 1.77 for the liquid on plate 5, are given as method 3 in Table V. This procedure with a cut temperature of 360° F. encountered the same difficulty already noted in indicating that the separation could not be accomplished with the L/V used, for the operating line intersected the lower terminal equilibrium curve before reaching the composition required.

Table VII summarizes the plate efficiencies for the upper section of the column (unit 1) as computed by plate-to-plate and graphical methods, and indicates a probable over-all plate efficiency of about 80 per cent. The use of the empirical equilibrium curves is less reliable and indicates a somewhat lower plate efficiency.

Plate Efficiency in Lower Section of Unit 1

In the lower section of the fractionating column (unit 1) the actual compositions of the vapor rising from plate 20 and of the liquid on plate 25 were used as the terminal conditions. Equilibrium curves calculated from these compositions were used in conjunction with an average operating line having a slope of 0.515. The results of the graphical solution are given as method 1 in Table VIII.

In applying the empirical equilibrium curves to this section of the column, the same procedure was followed as in the analysis of the top section of the unit. The slopes of 2.10 and 2.58, respectively, served as bases for determining the terminal equilibrium curves, and the operating lines used had the same slope of 0.515, as before. The results of this solution are indicated as method 2 in Table VIII.

The results for cut temperatures of 520°, 490°, 476°, and 464° F. are averaged in Table IX and indicate good agreement between the graphical procedures at an apparent over-all plate efficiency of about 33 per cent, being less than half that indicated for the upper section of the same column.

Plate Efficiency in Unit 2

Lewis and Wilde (17) tested a commercial column, 9 feet in diameter and containing ten plates spaced 20 inches apart; each of the plates above the feed was equipped with 115 Badger bell caps 6 inches in diameter. The total slot area per plate was 10 per cent of superficial cross section. Slots were 0.25 inch wide and 1 inch high, and the minimum seal was 1 inch. The vapor space above the top plate contained a partial condenser through which circulated cold oil to furnish reflux for the column, the remaining vapors passing to a total condenser. The column was part of a continuous battery of shell stills operated on a Midcontinent crude. The vapor fed to the column from the shell still entered below the bottom plate; the liquid fed to the column (the bottoms from the preceding shell still of the battery) entered on the eighth plate from the top.

The so-called true-boiling-point distillation curves of the overhead distillate (product) and of the liquid on plate 6 are represented by the solid lines in the upper section of Figure 11.

Lewis and Wilde computed plate efficiencies by utilizing

individual key components boiling in narrow ranges rather than the whole distillation curve, as has been done in the cases so far considered here. The use of such individual components makes the method entirely dependent upon the accuracy of a small section of the true-boiling-point curves which are generally not satisfactory for this purpose except when treating the more volatile fractions of less complexity (4).

On the basis of two key components, Lewis and Wilde found the average individual plate efficiency above the feed plate to be 65 per cent. However, for the two components so selected, deviations of from 0.15 to 0.26 mole fraction existed between the actual compositions and the corresponding computed compositions on certain plates when using this plate efficiency of 65 per cent. Lewis and Smoley (16) stated that such a plate efficiency is too low.

TABLE X. COMPARISON FOR DETERMINING PLATE EFFICIENCY OF PARTIAL CONDENSER IN UNIT 2

Temp. ° F.	Mole Fraction in Liquid in Equilibrium with Actual Vapor Leaving Partial Condenser	Mole Fraction in Actual Liquid Leaving Partial Condenser
242	0	0
290	0.048	0.045
300	0.071	0.066
310	0.117	0.113
320	0.162	0.160
330	0.223	0.208
340	0.326	0.321
350	0.425	0.425
360	0.547	0.541
370	0.669	0.650
380	0.791	0.792
390	0.900	0.914
400	0.976	0.975
436	1.000	1.000

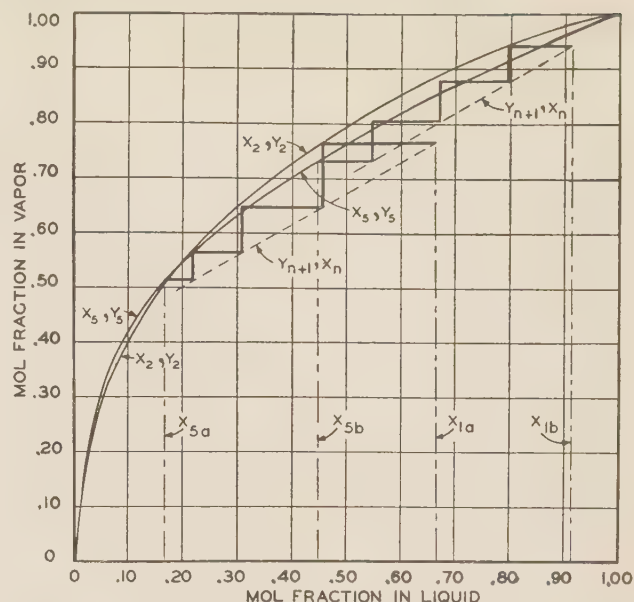


FIGURE 9. APPLICATION OF GRAPHICAL METHOD TO DATA OF UNIT 1

Determination of number of equilibrium plates required for same fractionation as was obtained between actual plates 2 and 5

totally condensed overhead distillate to the top equilibrium plate.

Using the average L/V of 0.815 (as computed from the data of Lewis and Wilde) for the operating lines and a Raoult's law correction factor of 0.88 (as used by Lewis and Wilde), the graphical solution of the problem gave the results indicated as method 1 in Table XI. The equilibrium plates are numbered in Table XI so that the partial condenser is equilibrium plate 1. Since this condenser is equivalent to an equilibrium plate, the efficiency of the actual plates should be determined by subtracting one from the number of equilibrium plates required, before dividing this number by the six actual plates in the section of the column.

The results obtained by applying the empirical curves of Figure 4 are given as method 2 in Table XI. The slopes of the distillation curves for the distillate and the liquid on plate 6 were 1.30 and 1.00, respectively, and corresponding curves were interpolated from Figure 4. The average slope of the operating line of 0.815 was used as before.

TABLE XI. PLATE EFFICIENCY IN UNIT 2^a

Method 1 = graphical calculation for distillate through plate 6 (partial condenser + 6 actual plates; Raoult's law correction factor = 0.88).
Method 2 = graphical calculation for distillate through plate 6, using empirical curves of Figure 4.

		Mole Fraction of Arbitrary Component								Actual x_6	y_6 in equilibrium with actual x_6	No. Equilibrium Plates	Plate Efficiency %
Cut Temp. ° F.	Method	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8				
408	1	0.9950	0.9900	0.9780	0.9550	0.9120	0.8450	0.7620	...	0.6160	0.7730	6.87	98
	2	0.9950	0.9900	0.9800	0.9605	0.9275	0.8800	0.8190	0.7410	0.6160	0.7710	7.62	110
396	1	0.9810	0.9645	0.9315	0.8775	0.8000	0.7120	0.6250	...	0.4640	0.6380	6.85	98
	2	0.9810	0.9560	0.9100	0.8300	0.7250	0.6060	0.5150	...	0.4640	0.6450	5.67	78
388	1	0.9460	0.9020	0.8330	0.7445	0.6490	0.5605	0.4885	...	0.3500	0.5260	6.48	91
	2	0.9460	0.8825	0.7810	0.6600	0.5500	0.4685	0.4150	...	0.3500	0.5300	5.25	71
380	1	0.8920	0.8125	0.7120	0.6065	0.5130	0.4385	0.3850	...	0.2430	0.4080	6.57	93
	2	0.8920	0.7800	0.6400	0.5150	0.4250	0.3700	0.3430	...	0.2430	0.4025	5.41	74
372	1	0.8270	0.7185	0.5990	0.4910	0.4075	0.3490	0.3110	...	0.1740	0.3240	6.66	94
	2	0.8270	0.6770	0.5250	0.4125	0.3450	0.3100	0.2990	...	0.1740	0.3050	6.45	91
364	1	0.7610	0.6300	0.5035	0.4015	0.3310	0.2870	0.2625	...	0.1330	0.2680	6.78	96
	2	0.7610	Operating line intersected equilibrium curve before reaching necessary x_6										
356	1	0.6810	0.5340	0.4080	0.3195	0.2620	0.2310	0.2150	...	0.1030	0.2220	6.56	93
	2	0.6810	Operating line intersected equilibrium curve before reaching necessary x_6										

^a Average reflux ratio (L/V) = 0.815.

TABLE XII. SUMMARY OF PLATE EFFICIENCIES FOR UNIT 2^a

Method	Av. No. Theoretical Plates	Av. Plate Efficiency %	Cut Temp. Included in Av. ° F.
Graphical calcn. for distillate through plate 6 (partial condenser + 6 plates) (Raoult's law correction factor = 0.88)	(6.68 - 1) ^b = 5.68	95	408, 396, 388, 380, 372, 364, 356
Graphical calcn. using empirical curves of Fig. 1	(6.08 - 1) ^b = 5.08	85	408, 396, 388, 380, 372
Av. individual plate efficiency by Lewis and Wilde (17)	.....	65 ^c	.....

^a Average reflux ratio (L/V) = 0.815.^b Considering the partial condenser equal to an equilibrium plate.^c This figure is too low, as was later recognized (16).

An average of the plate efficiencies indicated by method 1 (Table XII) showed an over-all efficiency of 95 per cent; use of the empirical equilibrium curves (method 2) indicated an over-all plate efficiency of about 85 per cent. If the condenser were included, the corresponding plate efficiencies would be 95 and 87 per cent.

When efforts were made to find the number of equilibrium plates between the partial condenser and actual plate 7, many of the cut temperatures chosen gave uncertain solutions; but when actual plate 6 was chosen as the bottom terminus of the section, the solutions were satisfactory. This behavior was due to the fact that an attempted analysis over a range equivalent to eight plates of 95 per cent efficiency was, in this case, too large a section of the column. It is generally true that the greater the slope of the distillation curves, the greater the curvature of the equilibrium curves. Inspection of the distillation curves originally presented by Lewis and Wilde for the individual plates of the column shows that the slopes of

the curves pass through a minimum at about 5 or 6, which should therefore be taken as a lower terminus in order that the equilibrium curves of intermediate plates may lie between those of the terminal plates.

Plate Efficiency in Unit 3

In order to eliminate several fundamental errors believed to have caused the deviations noted in Lewis and Wilde's work, Lewis and Smoley set up a laboratory column (16), 8 inches in diameter with 10 plates equally spaced 16 inches apart; each plate was occupied by one rectangular bubble cap 2 inches wide and extending entirely across the column. The column was operated at total reflux ($L/V = 1$) and was jacketed with a warm-air circulating system to minimize radiation losses.

Tests were run on a West Texas cracked naphtha with a distillation range of 70° to 480° F. Other runs were also made with other materials and with the addition of small amounts of foreign materials, used as "key components."

The results were analyzed by the type of calculation employing cut components (17), with the exception that the Raoult's law deviation factor was not fixed. In fact, several values were chosen for the factor, and the corresponding plate efficiencies were calculated; for the straight naphtha run a factor of 1.03 gave a good check, corresponding to a plate efficiency of about 80 per cent. But 1.03 differs from unity by less than the experimental error involved, and a correction factor of unity is sufficiently accurate.

When aniline, as the key component, was added to a naphtha of a slightly higher boiling range, a plate efficiency of

TABLE XIII. PLATE EFFICIENCY IN UPPER SECTION OF UNIT 3^a

Method 1 = graphical calculation for distillate through plate 6 (Raoult's law unmodified).

Method 2 = graphical calculation using empirical curves of Figure 4 for distillate through plate 6.

Mole Fraction of Arbitrary Component

Cut Temp. ° F.	Method	y ₁	y ₂	y ₃	y ₄	y ₅	y ₆	Actual x ₆	y ₆ in equilibrium with actual x ₆	No. Equilibrium Plates	Plate Efficiency %
250	1	0.9900	0.9710	0.9210	0.8240	0.6840	0.5360	0.5120	0.6400	5.30	80
	2	0.9900	0.9660	0.9000	0.7550	0.5600	0.3790	0.5120	0.6870	4.35	73
242	1	0.9700	0.9160	0.8040	0.6410	0.4660	0.3160	0.3310	0.4530	5.08	85
	2	0.9700	0.9000	0.7270	0.4875	0.2825	0.1600	0.3310	0.5630	3.68	61
236	1	0.9500	0.8670	0.7190	0.5320	0.3500	0.2180	0.2350	0.3430	5.05	84
	2	0.9500	0.8350	0.6050	0.3540	0.1850	0.0990	0.2350	0.3920	3.85	64
229	1	0.9200	0.8040	0.6230	0.4195	0.2500	0.1440	0.1020	0.1680	5.77	96
	2	0.9200	0.7500	0.4790	0.2500	0.1170	0.0615	0.1020	0.1920	4.44	74
222	1	0.8820	0.7310	0.5260	0.3160	0.1710	0.0910	0.0800	0.1370	5.43	90
	2	0.8820	0.6620	0.3790	0.1825	0.0870	0.0450	0.0800	0.1520	4.32	72

^a Average reflux ratio (L/V) = 1.0.TABLE XIV. PLATE EFFICIENCY IN LOWER SECTION OF UNIT 3^a

Method 1A = graphical calculation for plates 6 through 10 (unmodified Raoult's law).

Method 2A = graphical calculation using empirical curves of Figure 4 for plates 6 through 10.

Mole Fraction of Arbitrary Component

Cut Temp. ° F.	Method	y ₇	y ₈	y ₉	y ₁₀	y ₁₁	Actual x ₁₀	y ₁₀ in equilibrium with actual x ₁₀	No. Equilibrium Plates	Plate Efficiency %
311	1A	0.9800	0.9500	0.8785	0.7425	.....	0.7000	0.8625	3.12	78
	2A	0.9800	0.9600	0.9200	0.8475	0.7250	0.7000	0.8300	4.14	103
295	1A	0.9490	0.8915	0.7815	0.6175	.....	0.5700	0.7606	3.13	78
	2A	0.9490	0.9000	0.8110	0.6700	.....	0.5700	0.7350	3.54	89
278	1A	0.8600	0.7600	0.6170	0.4470	.....	0.4090	0.5990	3.11	78
	2A	0.8600	0.7450	0.5810	0.3985	.....	0.4090	0.5900	2.95	74
265	1A	0.7600	0.6400	0.4915	0.3340	.....	0.2350	0.3825	3.65	92
	2A	0.7600	0.6010	0.4190	0.2560	.....	0.2350	0.3920	3.16	79
259	1A	0.6750	0.5480	0.4020	0.2620	.....	0.1750	0.2960	3.76	94
	2A	0.6750	0.4980	0.3220	0.1850	.....	0.1750	0.3080	3.10	77
242	1A	0.3310	0.2150	0.1270	0.0680	0.0350	0.0250	0.0500	4.55	114
	2A	0.3310	0.1900	0.1020	0.0540	0.0300	0.0230	0.0450	4.37	109

^a Average reflux ratio (L/V) = 1.0.

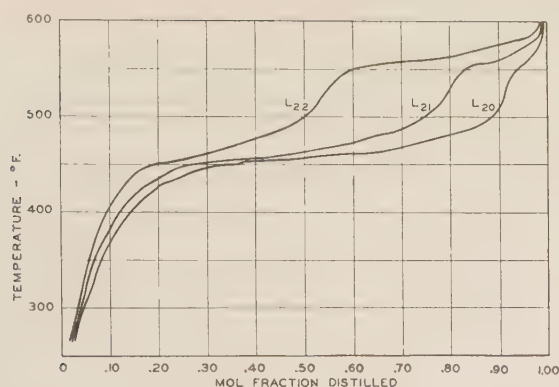


FIGURE 10. DISTILLATION CURVES FOR LIQUIDS IN LOWER SECTION OF UNIT 1 AS CALCULATED BY PLATE-TO-PLATE METHOD

Computed liquids leaving equilibrium plates 20, 21, and 22

95 per cent agreed with the experimental results. When pinene was added as the key component, a plate efficiency of 85 per cent was obtained in dilute solutions, and about 90 per cent in more concentrated solutions. Runs on benzene-toluene and benzene-toluene-xylene mixtures indicated plate efficiencies of about 59 and 75 per cent, respectively, using the same apparatus for all determinations.

For the present consideration of complex mixtures, the naphtha run made without any additional component is of greatest interest. The distillation curves for the overhead distillate (external reflux) and the liquids on the sixth and tenth plates of the column are shown in the lower section of Figure 11.

In applying the graphical method, the column is considered in two sections: (a) plates 1 through 6 and (b) plates 6 through 10. The distillation curves show the same characteristic of passing through a minimum slope as those of Lewis and Wilde, and the column requires more than six or eight equilibrium plates. Equilibrium curves were computed for the overhead distillate and the liquid on plates 6 and 10, using Raoult's law unmodified (Figure 12). Using L/V equal to 1, the equilibrium plates were stepped off, with the results given as method 1 in Table XIII.

Similarly, empirical equilibrium curves were applied to this same section, using the curves corresponding to slopes of 1.88 and 1.00, since the distillate and liquid on plate 6 had slopes of 1.88 and 0.58, respectively; the results of this computation are recorded as method 2 in Table XIII.

The lower section of the column was treated in the same manner, using both graphical procedures; the results are given in Table XIV.

The summary of these data (Table XV) indicates the close agreement between the results of the graphical method and those computed by Lewis and Smoley. The upper six plates of the column have an average over-all plate efficiency of 89 per cent, compared with 85 per cent for the lower four plates. A weighted average of these efficiencies indicates an over-all plate efficiency of 87.5 per cent, which is identical with the average of the individual plate efficiencies of 80, 85, 90, and 95 per cent reported by Lewis and Smoley for the various naphtha runs.

Using the single cut temperature of 242° F. throughout the column, from plates 1 to 10 as indicated in Figure 12, an average over-all plate efficiency of about 97 per cent is obtained. This higher average efficiency is in good agreement with the higher efficiencies obtained by Lewis

and Smoley and may be due to the choice of cut temperature or possibly to the low mole fraction of this cut in the liquid on plate 10 which was only 0.0250. Figure 12 shows clearly that equilibrium curves for plates 1 and 10 alone could not be used to give satisfactory results because the curve for plate 6 is not intermediate to 1 and 10.

The empirical results are satisfactory in the lower section of the column, covering only four plates. In the upper section of the column an equilibrium curve corresponding to a slope of 1.0 was used for a material with a computed slope of 0.6; this condition, coupled with the range of six plates covered, tends to introduce greater uncertainty in the results.

Plate Efficiency in Unit 4

A commercial unit tested by Goodliffe (11) contained twenty-two plates. The vapor fed to the column entered at a point below the twenty-second plate and at a temperature

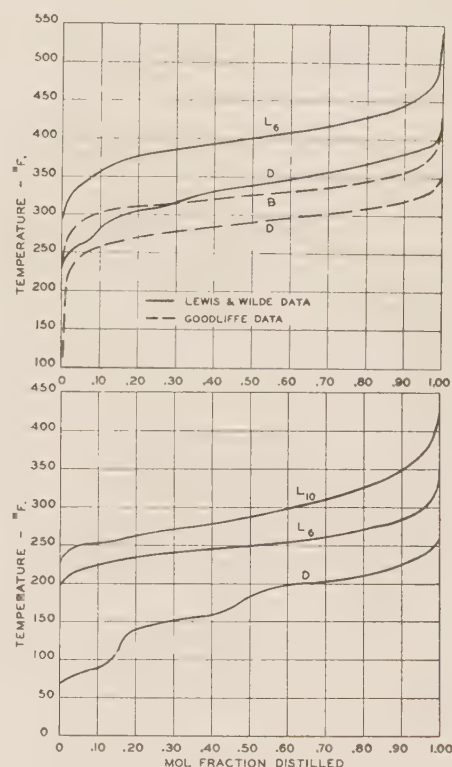


FIGURE 11. TRUE-BOILING-POINT DISTILLATION ANALYSES

(Above) Full lines show composition of distillate and liquid leaving plate 6 of unit 2; dashed lines show composition of distillate and bottom product of unit 4
(Below) Composition of distillate and liquid leaving plates 6 and 10 of unit 3

TABLE XV. SUMMARY OF PLATE EFFICIENCIES FOR UNIT 3^a

Method	Av. No. Equilibrium Plates	Av. Plate Efficiency %	Cut Temp. Included in Av. ° F.
1. Graphical calcn. for distillate through plate 6 (Raoult's law unmodified)	5.32	89	250, 242, 236, 229, 222
2. Graphical calcn. using empirical equilibrium curves of Fig. 4 for distillate through plate 6 (Raoult's law unmodified)	4.13	69	250, 242, 236, 229, 222
1A. Graphical calcn. for plates 6 through 10 (Raoult's law unmodified)	3.41	85	311, 295, 278, 265, 259
2A. Graphical calcn. using empirical equilibrium curves of Fig. 4 for plates 6 through 10	3.41	85	311, 295, 278, 265, 259
Av. of individual plate efficiencies reptd. by Lewis and Smoley (16)	..	87.5	.....

^a Average reflux ratio (L/V) = 1.0.

TABLE XVI. PLATE EFFICIENCY IN UNIT 4

Method 1 = graphical calculation from overhead distillate through bottoms (Raoult's law correction factor from Goodliffe's curve, 11).
 Method 2 = graphical calculation from overhead distillate through bottoms, using empirical curve of Figure 4 for atmospheric pressure.

Cut Temp. ° F.	Method	$\frac{L}{V}$	Mole Fraction of Arbitrary Component									Actual bottoms	Vapor in equilib- rium with bottoms	No. Equilib- rium Plates	Plate Effi- ciency %
			y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9				
333	1	0.605	0.9800	0.960	0.932	0.892	0.847	0.808	0.779	....	....	0.623	0.7850	6.8	18
	1	0.635	0.9800	0.9590	0.9255	0.8840	0.8400	0.7980	0.7640	....	....	0.6230	0.7850	6.40	16
	2	0.635	0.9800	0.9650	0.9470	0.9230	0.8950	0.8610	0.8440	0.7850	0.7500	0.6230	0.7760	8.26	25
330	1	0.605	0.9700	0.941	0.901	0.855	0.807	0.769	0.746	....	....	0.58	0.7525	6.7	17.6
	1	0.635	0.9700	0.9390	0.8950	0.8450	0.7960	0.7550	0.7235	....	....	0.5800	0.7525	6.10	15
	2	0.635	0.9700	0.9500	0.9250	0.8945	0.8565	0.8160	0.7760	0.7380	0.7050	0.5800	0.7440	7.84	23
328	1	0.605	0.9600	0.923	0.874	0.822	0.775	0.737	0.718	....	....	0.54	0.72	6.9	18.5
	1	0.635	0.9600	0.9200	0.8670	0.8100	0.7600	0.7200	0.6930	....	....	0.5400	0.7200	6.00	14
	2	0.635	0.9600	0.9325	0.8995	0.8590	0.8250	0.7800	0.7380	0.700	0.6700	0.5400	0.7110	7.71	22
323	1	0.605	0.9300	0.870	0.805	0.745	0.700	0.667	0.650	0.641	0.637	0.445	0.638	8.75	27
	1	0.635	0.9300	0.8665	0.7965	0.7330	0.6830	0.6480	0.6290	....	....	0.4450	0.6380	6.60	17
	2	0.635	0.9300	0.8850	0.8325	0.7775	0.7250	0.6800	0.6450	0.6180	0.6000	0.4450	0.6270	7.67	22

of 265° F. Open steam was introduced at this point, in addition to that carried in the vapor feed. The vapors from the top plate were passed through a partial condenser and water separator to furnish reflux for the column, and the remaining vapors were totally condensed as the overhead product. Since plate temperatures in the column varied from 219° F. at the bottom plate to 207° at the top plate, it is apparent that many of the trays were water-flooded, especially in view of the fact that the partial pressure of the steam was about 700 mm. The hydrocarbon partial pressure at the top of the column was 144 mm.; that at the bottom was 123 mm.

Goodliffe analyzed his data by means of plate-to-plate equations (29) for individual heat and material balances. For his equilibrium data Goodliffe used Raoult's law and applied correction factors obtained by experimental equilibrium vaporizations of the samples withdrawn from the plates of the column. These values obtained for the correction factor were averaged for each cut component and plotted as a function of boiling point. Many of these factors that went into the determination of one of the averaged points varied from

the average by amounts greater than the total range of the curve, and the correction factors so obtained have no more significance than those of Brown and Caine (1).

Goodliffe (11) computed over-all plate efficiencies on the basis of key components of 18° F. boiling range each, using a simplified procedure (27), and arrived at a value of 3.88 equilibrium plates to be equivalent to the 21 actual plates between the first and twenty-second, with $L/V = 0.605$. The average over-all plate efficiency, then, was 3.88/21, or 18.5 per cent, an extremely low value due to poor operating conditions with such large amounts of water present on the plates. In the earlier advance copy (11A) a slightly higher reflux ratio ($L/V = 0.635$) was used in the calculation of plate efficiency, and 3.36 equilibrium plates were indicated, corresponding to a plate efficiency of 16 per cent.

In applying the graphical binary mixture method of computation, the intention was primarily to compare this method with the plate-to-plate calculation used by Goodliffe (11A). Consequently Goodliffe's identical reflux ratios and equilibrium data were employed without variation. The equilibrium curves for the overhead product and for the bottom product, taken as the terminal conditions, were calculated for the indicated partial pressures from the distillation curves reported by Goodliffe as shown in dashed lines on the upper section of Figure 11. The number of equilibrium plates was determined by the graphical method, using values for L/V of 0.635 (11A) and 0.605 (11). The results are given as method 1 in Table XVI.

The slopes of the distillation curves of the materials on the plates of this column also go through a minimum, but the amount of fractionation accomplished by seventeen of the twenty-two plates is so small (equivalent to only about two equilibrium plates) that satisfactory results are obtained over the entire range of plates.

In order to obtain plate efficiencies for the same twenty-one plates utilized by Goodliffe, three equilibrium plates were subtracted from the total number of equilibrium plates required by the graphical method (Table XVI) to allow for the reboiler, partial condenser, and top plate.

The resulting plate efficiencies average 15.5 and 20.3 per cent, compared with 16 and 18.5 per cent computed by Goodliffe for the two reflux ratios. Using the average plate efficiency of the top or first plate of 83 per cent as computed by Goodliffe (11) and considering the condenser and boiler as equivalent to one plate each, the corresponding over-all plate efficiencies average 16.6 and 21.2 per cent, respectively. The latter figure is reduced to 18.9 per cent if the 323° F. cut temperature is omitted.

The empirical equilibrium curves were applied to these

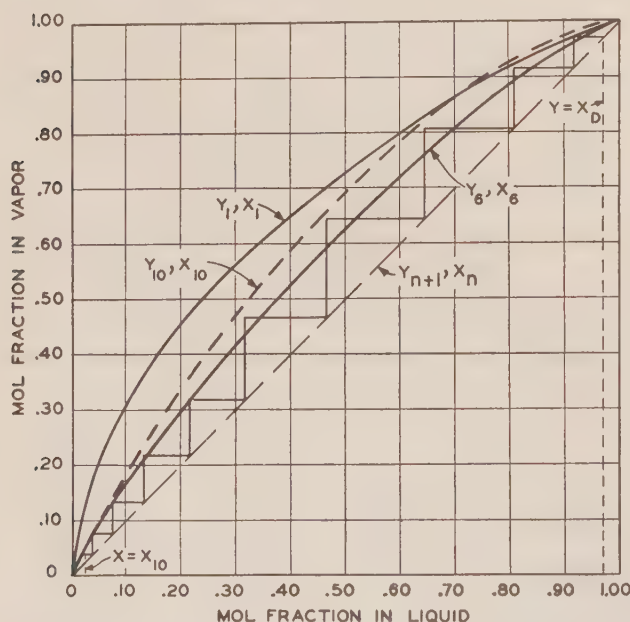


FIGURE 12. EQUILIBRIUM CURVES COMPUTED BY RAOULT'S LAW UNMODIFIED AND GRAPHICAL CALCULATION OF THE NUMBER OF EQUILIBRIUM PLATES IN UNIT 3 USING CUT TEMPERATURE OF 242° F. FROM DISTILLATE TO PLATE 10 WITH EQUILIBRIUM CURVES FOR PLATES 1, 6, AND 10

same data but without making any allowance for the low partial pressure of hydrocarbons. Since the top and bottom materials had distillation curves with slopes of 0.75 and 0.62, respectively, the empirical curve corresponding to a slope of 1.0 was used. The results, expressed as method 2 in Table XVI, show a total of 7.96 equilibrium plates, or 4.96 for the 21 actual plates under consideration, or a plate efficiency of about 23 per cent, which is not directly comparable for the reason stated.

Although individual plate efficiency, as defined by Murphree (20), and the highly refined methods for computing individual plate efficiencies are of most interest from a theoretical standpoint, the over-all average plate efficiency is practically of greater convenience in the design of fractionating columns, and can be determined with greater confidence on commercial equipment. The individual plate efficiencies, as computed by Goodliffe (11), vary from -50 to +81 per cent for the same components on different plates, and from -50 to +164 per cent for different components on the same plate. These discrepancies are probably due to difficulties in obtaining representative samples, particularly as Goodliffe attempted to sample the liquid on the plate of the column rather than to obtain a sample of the liquid overflowing from the plate to the next lower plate. It is better practice to define an equilibrium plate in terms of the average composition of the vapor leaving that plate and the composition of the liquid overflowing from that plate.

Since the average over-all plate efficiency can be determined satisfactorily by the graphical binary mixture method described over a series of not more than six or eight equilibrium plates, this method offers a convenient and reliable procedure for determining plate efficiency in petroleum fractionating columns without the necessity of taking samples from every plate.

Application to Design

If the over-all average plate efficiency is known, the number of actual plates required may be determined by dividing the number of equilibrium plates by the average over-all plate efficiency. In designing equipment, the required number of equilibrium plates may be determined by the graphical method described, by estimating or arbitrarily fixing the distillation characteristics desired in the overhead distillate and in the next lowest side stream as removed from the column; this can usually be done in a reasonably satisfactory manner by consideration of the distillation characteristics of the crude or feed to the column and the desired specifications in the overhead product. Equilibrium curves are then constructed for the products so determined. The slope of the operating line is determined from a heat and material balance over the column. The required number of equilibrium plates can then be computed readily in the manner described.

For the first approximation the empirical equilibrium curves shown in Figure 4 are more convenient, since they can be estimated directly from the slope of the distillation curves. If it is desired to base the computations upon A. S. T. M. distillation data, similar curves are available (13).

Acknowledgment

The plant data and samples for unit 1 were kindly furnished by the Development Department of the Union Oil Company of California, through E. G. Ragatz.

Nomenclature

D = distillate withdrawn as overhead product, moles; used as subscript to signify overhead product
 L = liquid, moles
 V = vapor, moles
 B = bottom product, moles; used as subscript to signify bottom stream

R = reflux returned to top plate, moles; used as subscript to signify reflux stream
 K = equilibrium constant for a particular component at temp. and total pressure of equilibrium
 P = total pressure
 p = vapor pressure of any component at temp. of equilibrium
 t = temp., ° F.
 x = mole fraction of any component in liquid phase
 y = mole fraction of any component in vapor phase
 a, b, c = individual components, of which a is most volatile, moles; used as subscripts to refer to individual components
 1, 2, . . . n = First, second, third . . . n th plate of a column, from top down

Bibliography

- (1) Brown and Caine, *Trans. Am. Inst. Chem. Engrs.*, **21**, 91 (1928).
- (2) Brown and Coats, *Natl. Gasoline Assoc. Am., Proc. 7th Ann. Convention*, 1928; Univ. Mich., *Dept. Eng. Research, Circ. Series 2* (1928).
- (3) Brown and Souders, *Trans. Am. Inst. Chem. Engrs.*, **30**, 447 (1934).
- (4) Brown, Souders, Nyland, and Hesler, *IND. ENG. CHEM.*, **27**, 383 (1935).
- (5) Cope and Lewis, *Ibid.*, **24**, 498 (1932).
- (6) Fenske, *Ibid.*, **24**, 482 (1932).
- (7) FitzSimons and Bahlke, *Am. Petroleum Inst., Bull.*, **11**, 70 (1930).
- (8) Fortsch and Whitman, *IND. ENG. CHEM.*, **18**, 795 (1926).
- (9) Garton and Huntington, *Refiner Natural Gasoline Mfr.*, **14**, 60 (1935).
- (10) Gilliland, *IND. ENG. CHEM.*, **27**, 260 (1935).
- (11) Goodliffe, *Trans. Inst. Chem. Engrs.* (London), **12**, 107 (1934).
- (11A) *Ibid.*, Advance copy, March 21, 1934, 3-31; *Chem. Abs.*, **28**, 4875 (1934).
- (12) Hausbrand, "Principles and Practice of Industrial Distillation" (tr. by Tripp), London, Chapman and Hall, 1925.
- (13) Katz and Brown, *IND. ENG. CHEM.*, **25**, 1373 (1933).
- (14) Leslie, Geniesse, Legatski, and Jagrowski, *Ibid.*, **18**, 45 (1926).
- (15) Lewis and Matheson, *Ibid.*, **24**, 494 (1932).
- (16) Lewis and Smoley, *Am. Petroleum Inst., Bull.*, **11**, 73 (1930).
- (17) Lewis and Wilde, *Trans. Am. Inst. Chem. Engrs.*, **21**, 99 (1928).
- (18) Maberry and Young, *J. Am. Chem. Soc.*, **28**, 426 (1906).
- (19) McCabe and Thiele, *IND. ENG. CHEM.*, **17**, 605 (1925).
- (20) Murphree, *Ibid.*, **17**, 747, 960 (1925).
- (21) Obryadchikov, *Ibid.*, **24**, 1155 (1932).
- (22) Obryadchikov and Karaseva, *Aznefteizdat*, 1932.
- (23) Peters and Obryadchikov, *Neftyanoe Khozyaistvo*, **24**, 50 (1933).
- (24) Sorel, "Distillation et rectification industrielles," Paris, 1893.
- (25) Souders, Selheimer, and Brown, *IND. ENG. CHEM.*, **24**, 517 (1932).
- (26) Thiele and Geddes, *Ibid.*, **25**, 289 (1933).
- (27) Underwood, *J. Soc. Chem. Ind.*, **52**, 223T (1932).
- (28) Underwood, *Trans. Inst. Chem. Engrs.* (London), **10**, 112 (1932).
- (29) *Ibid.*, **12**, 136 (1934).
- (30) Wilson, O. G., Jr., *IND. ENG. CHEM.*, **19**, 825 (1927).
- (31) Wilson and Bahlke, *Ibid.*, **16**, 115 (1924).
- (32) Young, *Proc. Roy. Irish Acad.*, **38**, 65 (1928).

RECEIVED May 9, 1936. Presented before the Division of Petroleum Chemistry at the 90th Meeting of the American Chemical Society, San Francisco, Calif., August 19 to 23, 1935.

PRINTED IN U. S. A.

